Chapter 12
Special Topics

12-1. Scope

This chapter provides general guidance in recognizing and treating special conditions which can be encountered in rock foundations that cause construction or operation problems. These conditions are likely to be encountered only within certain regions and within certain rock types, but geotechnical professionals should be aware of the potential problems and methods of treatment. This chapter is divided into three topic areas: karst, pseudokarst, and mines which produce substantial underground cavities; swelling and squeezing rock, much of which may be described as a rock but treated as a soil; and gradational soil-rock contacts, rock weathering, saprolites, and residual soils which make determination, selection, and excavation of suitable bearing elevations difficult.

Section I
Karst, Pseudokarst, and Mines

12-2. Cavities in Rock

A topic of concern in many projects involving rock excavation is whether or not there are undetected cavities below an apparently solid bedrock surface or whether cavities could develop after construction. These cavities may occur naturally in karst or pseudokarst terrains, may be induced by human interference in natural processes, or they may be totally due to man's activities. The term "cavities" is used since it covers all sizes and origins of underground openings of interest in rock excavations.

a. Cavity significance. The presence of cavities has a number of rock engineering implications, including:

(1) Irregular or potentially irregular bedrock topography due to collapse or subsidence and associated unpredictable bearing surface elevations.

(2) Excavation difficulties, with extensive hand-cleaning, grouting, and dental treatment requirements.

(3) Questionable support capacity with a potential for collapse or subsidence over cavities, or settlement of debris piles from prior collapses, all of which may be concealed by an apparently sound bedrock surface.

(4) Ground water flow problems, with requirements for tracing flow paths, or sealing off or diverting flows around or through the project area. Surface water flows may be affected by underground cavities, sometimes by complete diversion to the subsurface.

(5) Contaminants may flow rapidly into open channels, with minimal natural filtration and purification, possibly contaminating local water supplies.

b. Problem rocks.

(1) Most natural and induced cavities develop in soluble rocks, most notably limestone, dolomite, gypsum, and rock salt. Typical karst conditions develop in limestones and dolomites by solution-widening of joints and bedding planes caused by flowing ground water. Eventually, this process develops into a heterogeneous arrangement of cavities with irregular sinkholes occurring where cavity roofs have collapsed. The amount of solution that occurs in limestone and dolomite would be negligible in the lifetime of a typical project. Hence, existing cavities are the major concern.

(2) Gypsum and anhydrite are less common than limestones, but they have the additional concern of solution and collapse or settlement during the useful life of a typical structure. Flow of ground water, particularly to water supply wells, has been known to dissolve gypsum and cause collapse of structures. Rock salt is probably one of the most soluble of common geologic materials, and may be of concern in some areas, particularly along the Gulf of Mexico, the Michigan Basin, and in central Kansas. While natural occurrences of cavities in rock salt are rare, cavities may have been formed by solution mining methods, and collapse or creep has occurred in some of the mined areas.

(3) Pseudokarst terrain is an infrequently encountered form that appears to be classic karst topography, but occurs in a different geologic environment. Cavities and sinkholes can occasionally occur in lava flow tubes, or in poorly cemented sandstones adjacent to river valleys or coastlines. The same basic engineering problems and solutions apply to pseudokarst as to karst topography, but generally on a less severe scale. Care should be taken to avoid attributing surface features to pseudokarst conditions, when true karst conditions in lower rock strata may be the actual cause.

c. Mining activities. Mining is the principle cause of human-induced cavities, and subsidence or collapse over old mines is one of the oldest forms of surface disruption caused by man. Coal with occurrences shown in

Figure 12-1 is probably the most common material extracted by underground mining, although nearly any valuable mineral may have been mined using any scale of mining operation. The mines typically follow beds or ore bodies that are relatively easy to follow using stratigraphic or structural studies. The actual locations of mined cavities may be more difficult to determine. Mines in recent times generally have excellent layout maps available, but older mines may not be well documented. In some cases, small scale prospect operations may be totally obscured until excavations are at an advanced stage.

12-3. Investigations

Cavities are difficult to detect, and are undiscovered until exposed by construction excavations. A combination of detailed preconstruction investigations and construction investigations should be anticipated in potential cavity areas. In this respect, karst topography develops in relatively predictable regions of limestones and dolomites, as shown in Figure 12-2 and Table 12-1. However, the occurrence of cavities on a local scale is more difficult to determine, and many significant cavities can be missed by a typical exploration program. The inability to detect specific cavities also holds true for pseudokarst terrains, rock salt, gypsum, and mine cavities. The Geotechnical Investigations Manual, EM 1110-1-1804, provides guidance on the screening of an area for sinkholes, anhydrites or gypsum layers, caves, and area subsidence.

a. Initial site investigations. Geophysics may be of some use in initial site investigations in locating larger cavities, but may miss smaller ones. Remote sensing using air photos, infrared imagery, and side-looking radar are useful in determining trends of cavities and jointing in an area, as well as determining structural geology features associated with rock salt exposures. Detailed joint strike and dip mapping, in some cases by removing site overburden, may be very useful in predicting the trends of known cavities which follow joints. In some cases,

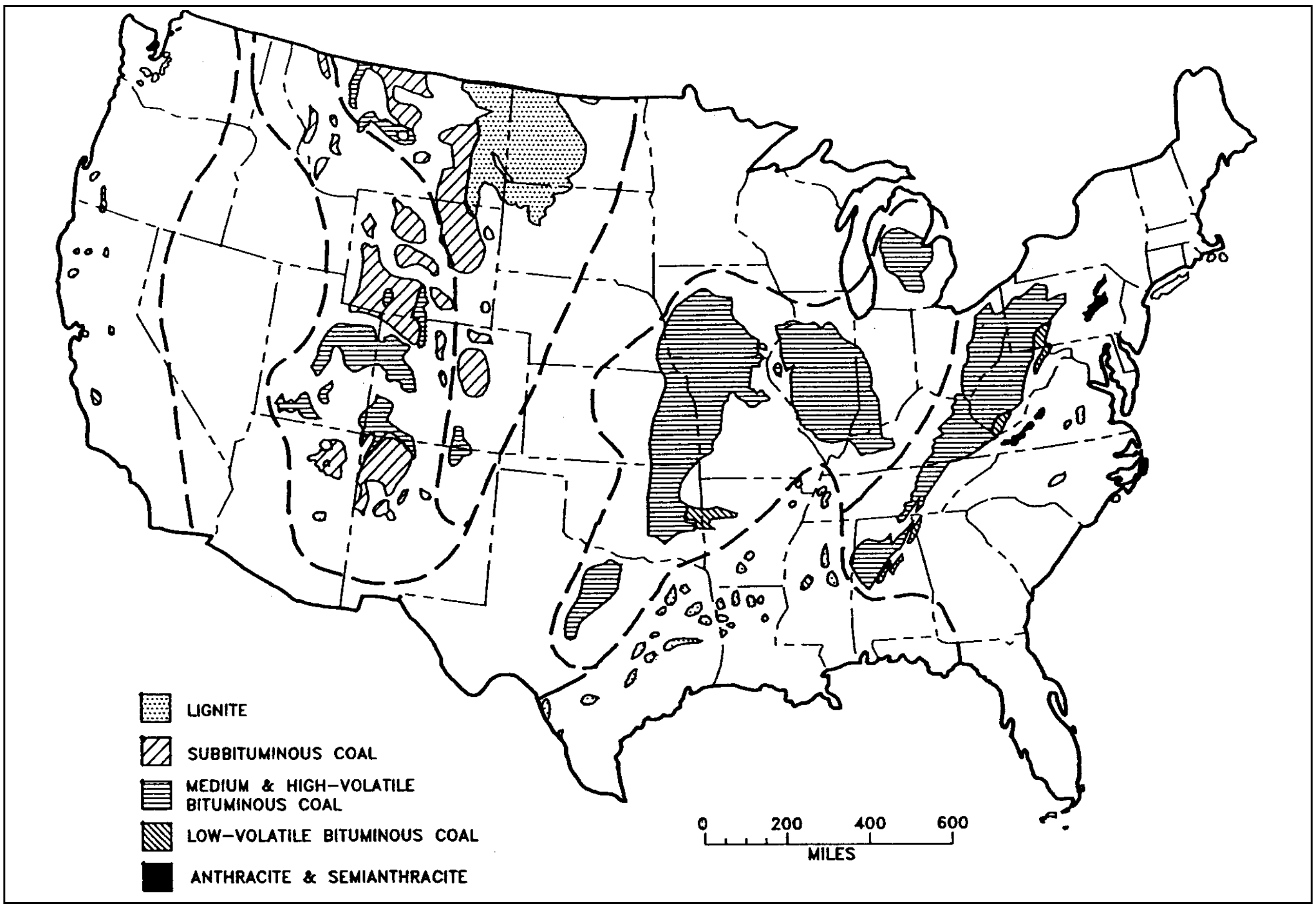

Figure 12-1. Location of coal fields in the United States

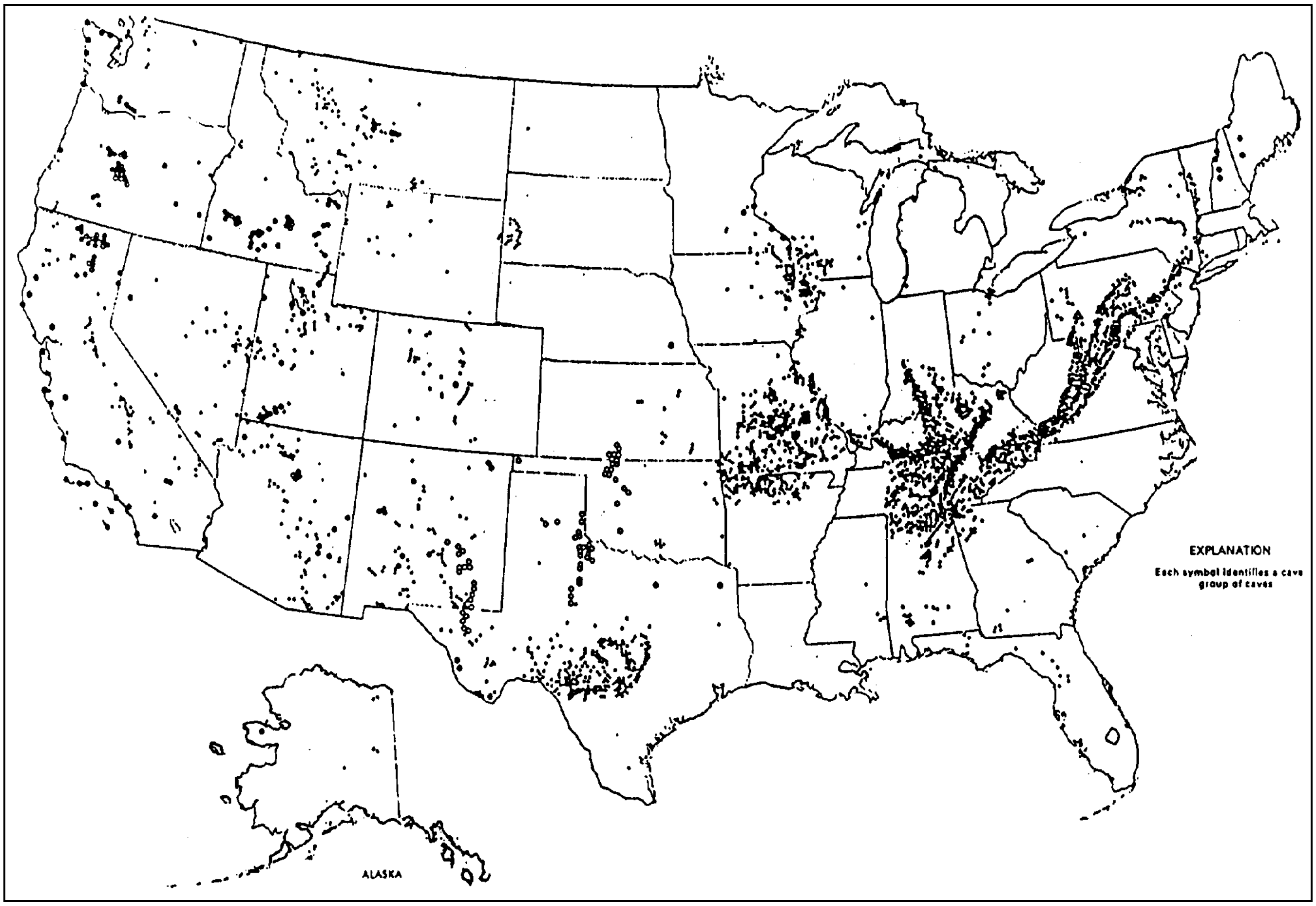

Figure 12-2. Location of cavern areas in the United States

hydrologic testing using piezometers, dye flow tracers, and pump tests may help determine permeabilities and probable flow paths along cavities. In the case of mines, stratigraphic analysis of economic minerals and ore body studies, along with studies of mining company records and Government documents associated with the mine, can help in determining the mine layout. Surveys from inside mines are desirable, but may not be possible due to dangerous conditions. Borehole cameras may be used to determine the size and condition of otherwise inaccessible mines. Table 12-2 shows several exploration and investigation methods which may be of more value in detection of cavities.

b. Cavity detection. Since cavity occurrence is difficult to determine on a local scale, the only practical solution, after initial site studies, is to place a test boring at the location of each significant load-bearing member. Such an undertaking is costly, but represents the only reasonable approach in areas of high concern.

12-4. Alternative Solutions

A number of techniques/methods are available for addressing design and construction problems associated with project sites where cavities are present. The following provides a brief listing of alternative techniques.

a. Avoid the area for load-bearing use if possible.

b. Bridge the cavity by transferring the loads to the cavity sides.

c. Allow for subsidence and potentially severe differential settlements in the design of the foundation and structure.

d. Fill in the cavities to minimize subsidence, prevent catastrophic collapse, and prevent progressive enlargement. Support piers or walls may be used for point supports in larger cavities, or cavities may be filled

Table 12-1
Summary of Major Karst Areas of the United States

Karst Area	Location	Characteristics
Southeastern coastal plain	South Carolina, Georgia	Rolling, dissected plain, shallow dolines, few caves; Tertiary limestone generally covered by thin deposits of sand and silt.
Florida	Florida, southern Georgia	Level to rolling plain: Tertiary, flat-lying limestone; numerous dolines, commonly with ponds; large springs; moderate sized caves, many water filled.
Appalachian	New York, Vermont, south to northern Alabama	Valleys, ridges, and plateau fronts formed south of Palaeozoic limestones, strongly folded in eastern part; numerous large caves, dolines, karst valleys, and deep shafts; extensive areas of karren.
Highland Rim	central Kentucky, Tennessee, northern Georgia	Highly dissected plateau with Carboniferous, flat-lying limestone; numerous large caves, karren, large dolines and uvala.
Lexington-Nashville	north-central Kentucky, central Tennessee, south eastern Indiana	Rolling plain, gently arched; Lower Palaeozoic limestone; a few caves, numerous rounded shallow dolines.
Mammoth Cave-Pennyroyal Plain	west-central, southwestern Kentucky, southern Indiana	Rolling plain and low plateau; flat-lying Carboniferous rocks; numerous dolines, uvala and collapse sinks; very large caves, karren developed locally, complex subterranean drainage, numerous large “disappearing” streams.
Ozarks	southern Missouri, northern Arkansas	Dissected low plateau and plain; broadly arched Lower Palaeozoic limestones and dolomites; numerous moderate-sized caves, dolines, very large springs; similar but less extensive karst in Wisconsin, Iowa, and northern Illinois.
Canadian River	western Oklahoma, northern Texas	Dissected plain, small caves and dolines in Carboniferous gypsum.
Pecos Valley	western Texas, southeastern New Mexico	Moderately dissected low plateau and plains; flat-lying to tilted Upper Palaeozoic limestones with large caves, dolines, and fissures; sparse vegetation; some gypsum karst with dolines.
Edwards Plateau	southwestern Texas	High plateau, flat-lying Cretaceous limestone; deep shafts, moderate-sized caves, dolines; sparse vegetation.
Black Hills	western South Dakota	Highly dissected ridges; folded (domed) Palaeozoic limestone; moderate-sized caves, some karren and dolines.
Kaibab	northern Arizona	Partially dissected plateau, flat-lying Carboniferous limestones; shallow dolines, some with ponds; few moderate-sized caves.
Western mountains	Wyoming, north western Utah, Nevada, western Montana, Idaho, Washington, Oregon, California	Isolated small areas, primarily on tops and flanks of ridges, and some area in valleys; primarily in folded and tilted Palaeozoic and Mesozoic limestone; large caves, some with great vertical extent, in Wyoming, Utah, Montana, and Nevada; small to moderate-sized caves elsewhere; dolines and shafts present; karren developed locally.

Table 12-2
Effectiveness of Cavity Investigation Techniques

		Investigation Method Considered[1]						
Cavity Type	Increased Borings	Geophysics	Remote Sensing	Piezometers	Pump Tests Dye Flow Tests	Discontinuity Analysis	Borehole Cameras	Mine Record Studies
Anhydrite Gypsum	2	1	2	1	1	3	1	2
Karst	5	4	4	2	3	5	5	1
Salt	2	3	3	1	1	1	2	3
Mines	4	4	4	1	1	1	5	5
Lava Tubes	4	2	4	2	2	1	3	1

Note:
1. Ratings: Grade from 1 = not effective to 5 = highly effective

with sand, gravel, and grout. Cement grout can be used to fill large cavities to prevent roof slabs from falling, eliminating a potential progression to sinkholes. Grout also can fill cavities too small for convenient access, thereby reducing permeability and strengthening the rock foundation.

e. Avoid placing structures over gypsum, salt, or anhydrite beds where seeping or flowing water can rapidly remove the supporting rock.

f. Plan for manual cleaning of pinnacled rock surfaces with slush grouting and dental treatment of enlarged joints as shown in Figure 12-3. The exact extent of this work is difficult to predict prior to excavation.

g. Control surface and ground-water flow cautiously. Lowering of the water table has induced collapses and the formation of new sinkholes in previously unexpected areas. Surface drainage in most karst areas is poorly developed, since most drainage has been to the subsurface.

Section II
Swelling and Squeezing Rock

12-5. General

The case of swelling or squeezing rock represents yet another special problem. In such cases the rock foundation changes after it is exposed or unloaded, and the rock expands (increases in apparent volume) horizontally or vertically. There are at least five mechanisms which can cause swelling rock. Swelling may be result of a single mechanism or a combination of several interacting mechanisms. The five common mechanisms of swelling rock include elasto-plastic rebound (or heave), cation hydration, chemical reaction, loss of internal strength (creep), and frost action. Some of these mechanisms occur most commonly in certain rock types. Each category is discussed individually.

12-6. Rebound

Elasto-plastic rebound is the expansion of rock due to the reduction or removal of external forces acting upon the rock mass. In some cases, especially in areas with a high horizontal stress field, removal of as little as a few feet of rock or soil may result in an expansion of the exposed rock. The expansion may be expressed as a general heave of the exposed rock or as a pop-up or buckling. This behavior frequently occurs in areas associated with glacial activity and can occur in most types of rock. In structural excavations where rebound may be a problem, the surface may be rapidly loaded with a weight equivalent to the overburden to prevent rebound of the rock. In many nonstructural open cut excavations, this type of swelling may be more of a minor maintenance problem than a serious concern.

12-7. Cation Hydration

Cation hydration is another mechanism for swelling that is most frequently associated with some argillaceous rocks.

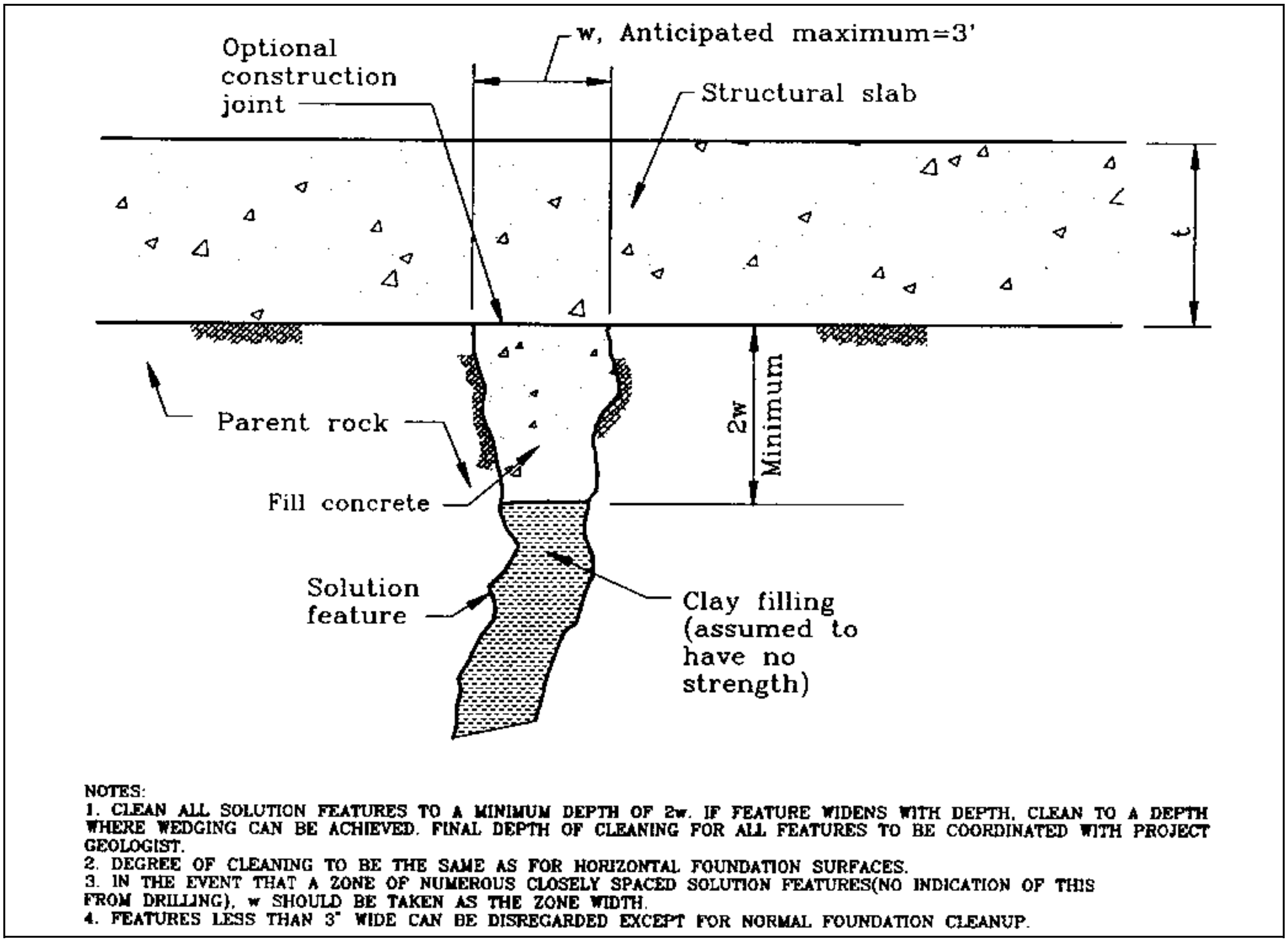

Figure 12-3. Criteria for treatment of solution-widened joints

The process refers to the attraction and adsorption of water molecules by clay minerals. Factors that contribute to this form of swell include poor cementation, desiccation and rewetting, unloading, and high clay mineral content; especially montmorillonite clay.

a. Problem rocks. Clay shale is the rock most commonly associated with swelling problems, and its principal mechanism of swell is cation hydration. Defined as shales that tend to slake easily with alternate wetting and drying, clay shales were overconsolidated by high loads in the past. Typically, clay shales were deposited in shallow marine or deltaic environments in Cretaceous or Paleocene times and contain a high percentage of swell prone montmorillonite mineral.

b. Other factors. Factors other than clay mineral type and content may also contribute to cation hydration induced swell. These factors include density, moisture content, rock mineral structure, loading history, and weathering.

(1) Density of the rock is an important indicator of swell. A 25 percent increase in the dry density of clay shales can more than double the maximum swell pressures developed in the material. Therefore a high density could indicate high swell pressure potential.

(2) Low moisture content can indicate a high swell potential, since there is more availability for water within the clay structure.

(3) The mineral structure of the clay shale can influence the magnitude and isotropy of the swell characteristics. A compacted mineral orientation typical of clay shales has most of the plate mineral faces in a “stacked” arrangement, with maximum swell potential normal to the mineral faces.

(4) The loading history can indicate the degree of preconsolidation that the shales have been subjected to in the past. Changes in the stress environment can be due to erosion, glaciation, stream downcutting, and engineering activities.

(5) Weathering of clay shales generally reduces the swell potential unless additional expansive clays are formed.

c. Excavation problems. Excavations in clay shale present special problems. If the excavated surface is allowed to dry, the material develops shrinkage cracks, and rebound-type swell induces a relative moisture reduction and density decrease. Water or moisture from concrete applied to this surface can induce swelling of the clay shale. Slope stability is another prominent problem in clay shales, since any excavation can result in renewed movement along older, previously stable slide planes. The presence of unfavorably oriented bentonite seams common in clay shales can present serious stability hazards.

d. Treatment methods. Preventive measures can include careful control of the excavation sequence, moisture control and surface protection, and favorable stratigraphic placement and orientation of the slopes and structures. Treatment methods are discussed in Chapter 11.

e. Field investigations. Field investigations should include checks for significant problem prone clay shale formations, some of which are listed in Table 12-3. Also, some indications of clay shale swell problems include hummocky terrain along river valley slopes, slides along road cuts, and tilting or cracking of concrete slabs or light structures. Slickensides in shale is another indicator of swelling potential. The presence of clay shales susceptible to cation hydration swelling in the project region should be determined very early in the exploration program.

f. Laboratory tests. Laboratory tests to determine engineering properties are similar to those for soil mechanics, and include clay mineral type and percentage analyses, Atterberg limits, moisture content, consolidation tests, and swell tests. In decreasing order, the significant swell producing clay minerals are montmorillonite, illite, attapulgite, and kaolinite. Atterberg limit tests can indicate the swelling nature of clay shale, with high plasticity indices correlating to high swell potential, as shown in Table 12-4. The method of determining the Atterberg limits of clay shale must be consistent, since air drying, blending, or slaking of the original samples may provide variable results. There are several methods of performing consolidation and swell tests on clay shales. These methods are summarized in Table 12-5.

12-8. Chemical-Reaction Swelling

Chemical-reaction swelling refers to a mechanism most commonly associated with Paleozoic black shales such as the Conemaugh Formation, or the Monongahela Formation in Pennsylvania. Swell develops when reactions such as hydration, oxidation, or carbonation of certain constituent minerals create by-products that results in volumes significantly larger than the original minerals. These reactions can result in large swelling deformations and pressures after excavation and construction. The conditions that are conducive to this type of swelling may not occur until after a foundation is in place, and similar conditions may not be reproduced easily in the laboratory to indicate that it may be a problem. Temperature, pressure, moisture, adequate reactants and, in some cases, bacterial action are critical parameters for reaction to occur.

a. Reactions. The transformation of anhydrite to gypsum is one of the more common reactions. In shales containing a substantial percentage of free pyrite, a similar reaction can occur. The oxidation of the pyrite can result in the growth of gypsum crystals or a related mineral, jarosite. The presence of sulphur bacteria can aid the reaction, and may be essential to the reaction in some cases. Sulfuric acid produced by the reaction may react with any calcite in the shale to increase the development of gypsum. The resulting growth of gypsum crystals causes the swelling, which can uplift concrete structures.

b. Treatment methods. Since the reactions are difficult to predict or simulate during exploration and design, it may be desirable to avoid placing structures on pyrite-bearing carbonaceous shales of Paleozoic age, since these rocks are the most common hosts for chemical-reaction swelling. If avoidance is not an option, the exposed surfaces may be protected from moisture changes by placing a sealing membrane of asphalt or some other suitable material. Shotcrete is not a suitable coating material since the sulfuric acid produced by the reaction can destroy it. The added source of calcium may even enhance the swelling reaction. Another preventive measure may be the application of a chemical additive which blocks the growth of gypsum crystals. Tests have indicated that

Table 12-3
Landslide-Susceptible Clay Shales in United States

Stratigraphic Unit	Description
Bearpaw shale	Upper Cretaceous; northern, eastern and southern Montana, central northern Wyoming, and southern Alberta, Canada; marine clay shale 600 to 700 ft; in Montana group.
Carlile shale	Upper Cretaceous; eastern Colorado and Wyoming, Nebraska, Kansas, and South Dakota, southeastern Montana and northeastern New Mexico; shale, 175 to 200 ft; in Colorado group.
Cherokee shale	Early Pennsylvanian; eastern Kansas, southeastern Nebraska, northwestern Missouri and northeastern Oklahoma; shale, 500 ft; in Des Moines group.
Claggett formation	Upper Cretaceous; central and eastern Montana, and central northern Wyoming; marine clay shales and sandstone beds, 400 ft; in Montana group.
Dawson formation	Upper Cretaceous-Lower Tertiary; central Colorado; nonmarine clay shales, siltstone and sandstone, 1000 ft.
Del Rio clay	Lower Cretaceous; southern Texas; laminated clay with beds of limestone; in Washita group.
Eden group	Upper Ordovician; southwestern Ohio, southern Indiana, and central northern Kentucky; shale with limestone, 250 ft; in Cincinnati group.
Fort Union group	Paleocene; Montana, Wyoming, North Dakota, northwestern South Dakota, and northwestern Colorado; massive sandstone and shale, 4000 ft +.
Frontier formation	Upper Cretaceous; western Wyoming and southern Montana; sandstone with beds of clay and shale, 2000 to 2600 ft; in Colorado group.
Fruitland formation	Upper Cretaceous; southwestern Colorado and northwestern New Mexico; brackish and freshwater shales and sandstones, 194 to 530 ft; late Montana age.
Graneros shale	Upper Cretaceous; eastern Colorado and Wyoming, southeastern Montana, South Dakota, Nebraska, Kansas and northeastern New Mexico; argillaceous or clayey shale, 200 to 210 ft; in Colorado group.
Gros Ventre formation	Middle Cambrian; northwestern Wyoming and central southern Montana; calcareous shale with conglomeratic and oolitic limestone, 800 ft.
Jackson group	Upper Eocene; Gulf Coastal Plain (southwestern Alabama to southern Texas); calcareous clay with sand, limestone, and marl beds.
Mancos shale	Upper Cretaceous; western Colorado, northwestern New Mexico, eastern Utah, southern and central Wyoming; marine, carbonaceous clay shale with sand, 1200 to 2000 ft; of Montana and Colorado age.
Merchantville clay	Upper Cretaceous; New Jersey; marly clay, 35 to 60 ft; in Matawan group.
Modelo formation	Upper Miocene; southern California; clay, diatomaceous shale, sandstone, and cherty beds, 9000 ft.
Monterey shale	Upper, middle and late lower Miocene; western California; hard silica-cemented shale and soft shale, 1000 ft +.
Morrison formation	Upper Jurassic; Colorado and Wyoming, south central Montana, western South Dakota, western Kansas, western Oklahoma, northern New Mexico, northeastern Arizona, and eastern Utah; marl with sandstone and limestone beds, 200 ft +.
Mowry shale	Upper Cretaceous; Wyoming, Montana and western South Dakota; hard shale, 150 ft; in Colorado group.
Pepper formation	Upper Cretaceous; eastern Texas; clay shale.
Pierre shale	Upper Cretaceous; North Dakota, South Dakota, Nebraska, western Minnesota, eastern Montana, eastern Wyoming, and eastern Colorado; marine clay shale and sandy shale, 700 ft; in Montana group.
Rincon shale	Middle or lower Miocene; southern California; clay shale with lime stone, 300 to 2000 ft.
Sundance formation	Upper Jurassic; southwestern South Dakota, Wyoming, central southern Montana; northwestern Nebraska; and central northern Colorado; shale with sandstone, 60 to 400 ft.
Taylor marl	Upper Cretaceous; central and eastern Texas; chalky clay, 1200 ft.
Thermopolis shale	Upper Cretaceous; central northern Wyoming, and central southern Montana; shale with persistent sandy bed near middle, 400 to 800 ft; in Colorado group.
Trinity group	Lower Cretaceous; Texas, south central and southeastern Oklahoma, southwestern Arkansas, and northwestern Louisiana; fine sand, gypsiferous marl and occasional limestone.
Wasatch formation	Lower Eocene; Wyoming, south central and eastern Montana, southwestern North Dakota, western Colorado, Utah, and northwestern New Mexico; sands and clay, 0 to 5000 ft +.

Table 12-4
Swell Potential and Atterberg Limits

	Swelling Potential		
Index Property	Low	Medium	High
Liquid Limit	30-40	40-55	55-90
Plastic Limit	15-20	20-30	30-60
Shrinkage Limit[1]	35-25	25-14	14-8
Free Swell[2]	20-40	40-70	70-180

Notes:
1. Poor Correlation to Swelling Properties.
2. Described by Katzir and David (1986).

diethylenetriamine penta (methylene phosphonic acid), substantially inhibited gypsum development under normally reactive conditions. Other similar crystal growth inhibitors may be useful in preventing chemical-reaction swelling.

12-9. Loss of Internal Strength

This swelling mechanism occurs most commonly when intact rock loses its internal bonding or cementation. The mechanism is commonly associated with extensive alteration in major faults occurring in granites, gneisses, and poorly-cemented sandstones under stress conditions commonly associated with tunneling projects, but it may be of concern in very deep, open excavations. The swelling acts primarily on side-walls as a type of slow continuous plastic deformation under a constant load. Problems caused by this swell mechanism are usually of more concern where close tolerances and long-term stability are critical.

12-10. Frost Action

Freezing can induce swelling or heaving of rock in excavations by the expansion of water within the rock mass. Although pore water freezing in porous rocks may be of some concern, the principal concern is freezing water in joints, bedding planes, and other openings in the rock. Since many of these discontinuities may have been relatively tight prior to freezing, a spalling effect from frost may induce a nonrecoverable bulking of the rock and reduction in strength of the rock mass in addition to the temporary uplift by freezing. Preventive measures can include limiting excavation of final grades to warmer seasons, moisture controls or barriers, and layers of soil or insulation blankets in areas of special concern.

12-11. Design Considerations

If rock in an excavation is found to have a swelling potential, it may not be a serious concern unless structures are to be placed on the rock surface. With structures, swell and differential swell must then be considered and preventive techniques used. Some foundation design techniques for handling swell problems are summarized in Table 12-6.

Section III
Soil-Rock Contacts

12-12. General

Some of the most difficult excavation problems occur in rock that has been severely weathered or altered. While it is generally assumed that bedrock will be easy to locate and identify, the assumption may not always be correct. In some cases, weathering can form a residual soil that grades into unweathered bedrock, with several rock-like soil or soil-like rock transitions in between. These residual soils, saprolites, and weathered rocks require special consideration, since they may have characteristics of both rock and soil which affect rock excavations and foundation performance.

12-13. Weathering Profiles

Chemical weathering is the primary cause of gradational soil-rock contacts, with the most prominent cases occurring in warm, humid climates. The result can be irregular or pinnacled rock covered by gradational materials composed of seamy, blocky rock, saprolite, and soil. The preferred case of an abrupt contact between soil and unweathered rock is not usually what is found. General descriptions of the zones in typical profiles for igneous and metamorphic rocks are given in Table 12-7. There are similarities in the development of these profiles. Weathering tends to dissolve the most soluble materials and alter the least stable minerals first, following rock mass discontinuities such as faults, joints, bedding planes, and foliations. The unweathered rock surface may be highly irregular due to solution and alteration along these openings. Engineering design and excavation considerations are dependent upon specific weathering profiles developed in certain rock types. These profiles include: massive igneous, extrusive igneous, metamorphic, carbonate, and shale.

a. Massive intrusive igneous profiles. Rocks typical of massive igneous profiles include granites and other

Table 12-5
Summary of Swell Potential Tests

Test Method	Test Procedure Summary	Remarks
Free-Swell Test	This specimen is over-dried, granulated and placed in a test tube. Water is added and the amount of volume expansion is recorded.	The rock structure is destroyed and the grain sizes are reduced.
Calculated-Pressure Test	An intact specimen is immersed in kerosene or mercury to determine its initial volume. The specimen is then placed in water and allowed to swell. If the specimen remains intact, the new volume can be determined by again immersing the specimen in mercury. Otherwise, the swell is recorded as the change in volume of the water-specimen system.	The loading and confining pressures are not representative of in-situ conditions.
Unconfined Swell Test	The specimen is placed in a container and ames dials are set to one or more axes of the specimen. Water is added and the axial expansion is recorded.	The loading and confining pressures are not representative of in-situ conditions.
Nominal Load Test	A specimen is inserted in a consolidometer, a nominal seating load is applied (generally 200 psf or 0.10 Kg/cm^2) and water added. The volume change is recorded by an ames dial.	The loading and confining pressures are not representative of in-situ conditions.
Calculated-Pressure Test	The specimen placed in a consolidometer and subjected to a calculated overburden pressure. Free access to water is then permitted and the volume expansion recorded. Modifications of this test included rebounding the specimen to the original void ratio.	
Constant-Volume Test	The specimen is inserted in a consolidometer and a seating load applied. Water is added, and pressure on the specimen increased such and pressure on the specimen increased such that the total volume change of the specimen is zero. The final pressure is taken as the "swell pressure".	Under in-situ conditions, the volume may change resulting in a reduced final pressure.
Double-Deadmeter Test	Two similar specimens are place in separate consolidometers. One specimen is subjected to calculated overburden pressures and the deformation recorded. The other specimen is allowed free access to water, is permitted to swell and then is subjected to overburden pressure. The difference in deformations or strain of the two specimens at the overburden pressure is considered the potential swell of the material.	Results are more typical of field conditions.
Triaxial Test	A specimen is consolidated to the in-situ pressure as evaluated by stress measurements of statistical analyses. Generally, the horizontal stress is greater than the applied vertical stress. The specimen is then allowed free access to water and the swell recorded.	This test is typical of field conditions, and can simulate high horizontal stress field.

Table 12-6
Design Techniques and Methods of Treatment for Swelling Rocks (after Linder 1976)

a. Waterproofing Below and Around Foundations: Though successful in preventing drainage into the strata directly below the foundation, this method does not consider evaporation. The technique is best employed to prevent desiccation of strata during construction.

b. Rigid-Box Design: The design of the foundation into separate reinforced concrete units or boxes that can withstand predicted stresses and deformations is a feasible yet expensive solution to swell.

c. Saturation and Control: Saturation of swell-susceptible strata before construction by ponding will help reduce swell after construction. However, if the water content is not maintained additional settlement will be experienced during the life of the structure. Also seasonal fluctuation of the availability of water may cause the structure to rise and fall periodically.

d. High Loading Points: As swell is a function of both deformation and pressure, it was reasoned that foundations with high unit loadings should experience less swell. However, such foundations have met numerous problems including uplift on footings. Such foundations also influence only a small volume below the footing and swell may be experienced due to swell of deeper strata.

e. Replacement of the Stratum: A drastic, expensive, yet totally effective procedure for near-surface strata.

f. Piers: The concept of placing the base of the foundation below swell susceptible strata or where water content changes are expected to be minimal has also been employed with varying success. Problems such as side friction and water changes induced by construction must be considered.

g. Flexible Construction: For light structures, the division of the structure into units which can move independently of each other can be a practical solution. Differential heave between units will cause no stress to the structure and minor repair work will assure continuing service.

h. Raised Construction: A little-used alternative is to place the structure on a pile system raised above the surface. This would allow normal air circulation and evaporation below the structure and if drainage is properly designed should cause minimal disturbance to the water content of swell susceptible strata.

igneous rocks with relatively homogenous, isotropic texture. Since this type of rock has few or no bedding planes, foliations, or concentrations of minerals relatively susceptible to weathering, the existing joints, faults, and shear zones control the development of weathering. Stress-relief slabbing or sheeting joints subparallel to the ground surface also provide a path for chemical weathering, as shown in Figure 12-4. Saprolite (Zone IC in Figure 12-4) in this type of profile may retain the texture and orientation of the parent rock. Relict joints may still act as sliding-failure planes or preferred paths for ground water flow, so some of the parent rock's properties still apply to this material. The transition (Zone IIA) has the same slide failure and ground water concerns as with the saprolite, but the element of corestones becomes an additional concern. These are the hard, partially weathered spheroidal centers of blocks that can range from soft to relatively hard, and from small size to relatively large. The transition zone may require a modification of the excavation methods used, from purely mechanical soil excavation methods to the occasional use of explosives or hand-breaking. Corestones in this type of profile are generally spheroidal, which can cause difficulties in excavation and removal if they are relatively large.

b. Extrusive igneous profiles. Extrusive rocks such as basalt develop profiles and conditions similar to those found in massive igneous rocks. However, certain structural features common in basalts and tuffs make conditions extremely variable in some areas. For example, lava flow tubes and vesicular basalt may increase the weathering path in some zones. The nature of flow deposits may make rock conditions in excavations difficult to predict since there may be buried soil profiles and interbedded ash falls or tuffs which are more permeable than adjacent basalts. These complex permeable zones can increase weathering and store water under relatively high pressures. Also, soils in the upper horizons may have unpredictable engineering characteristics due to unusual clay minerals present from the weathering of highly ferromagnesian parent materials.

c. Metamorphic profiles. Since the structure or texture of metamorphic rocks can range from schistose to nearly massive gneissic, the weathering profiles can vary greatly, as illustrated in Figure 12-5. Foliations in the rocks and changes of the lithology enhance the variability that can be found in the weathering profiles in metamorphics. The results are differences in the depths

Table 12-7
Description of a Typical Weathering Profile

	Zone	Description	RQD[1] (NX Core, percent)	Percent Core Recovery[2] (NX Core)	Relative Permeability	Relative Strength
I Residual Soil	1A-A Horizon	- top soil, roots, organic material zone of leaching and eluviation may be porous	--	0	medium to high	low to medium
	1B-B Horizon	- characteristically clay-enriched also accumulations of Fe, A1 and Si hence may be cemented - no relict structures present	--	0	low	commonly low (high if cemented)
	1C-C Horizon	- relict rock structures retained - silty grading to sandy material - less than 10 percent core stones - often micaceous	0 or not applicable	generally 0-10 percent	medium	low to medium (relict structures very significant
II Weathered Rock	IIA-Transition (from residual soil or saprolite to partly weathered rock)	- highly variable, soil-like to rock-like - fines commonly fine to coarse sand (USS) - 10 to 90 percent core stones - spheroidal weathering common	variable, generally 0-50	variable, generally 10-90%	high (water losses common)	medium to low where waste structures and relict structures are present
	IIB-Partly weathered rock	- rock-like, soft to hard rock - joints stained to altered - some alteration of feldspars and micas	generally 50-75 percent	generally >90 percent	medium to high	medium to high[2]
III Unweathered Rock		- no iron stains to trace long joints - no weathering of feld- and micas	>75 percent (generally >90 percent)	generally 100 percent	low to medium	very high[2]

Notes:
1. The descriptions provide the only reliable means of distinguishing the zones.
2. Considering only intact rock masses with no adversely oriented geologic structure.

of weathering profiles developed over each lithology, in some cases up to 50 meters of difference vertically in just a few feet horizontally (Deere and Patton 1971). Intrusive dikes commonly found in metamorphic terrains may either be more or less resistant to weathering than the surrounding rock, forming either ridges or very deep weathering profiles. Problems in this type of profile include slide instability along relict foliation planes, highly variable depth to unweathered bedrock, and potentially high-pressure ground water storage in faults or behind intrusive dikes.

d. Carbonate profiles. Carbonate rock weathering was previously discussed in relation to karst development within the rock mass. The same weathering conditions may affect the surface of the rock. Carbonate rocks

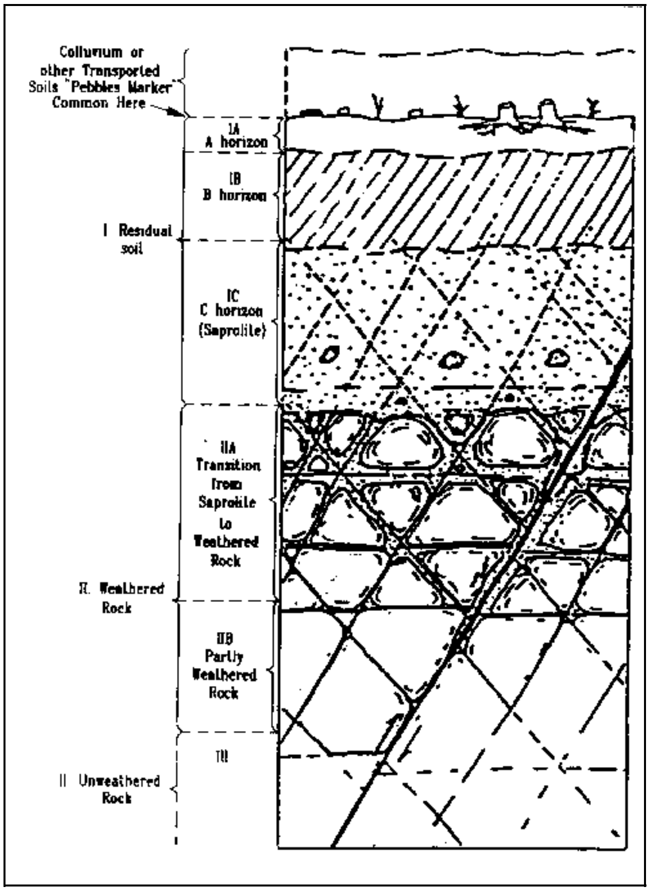

Figure 12-4. Typical weathering profile for intrusive igneous rocks (from Deere and Patton 1971)

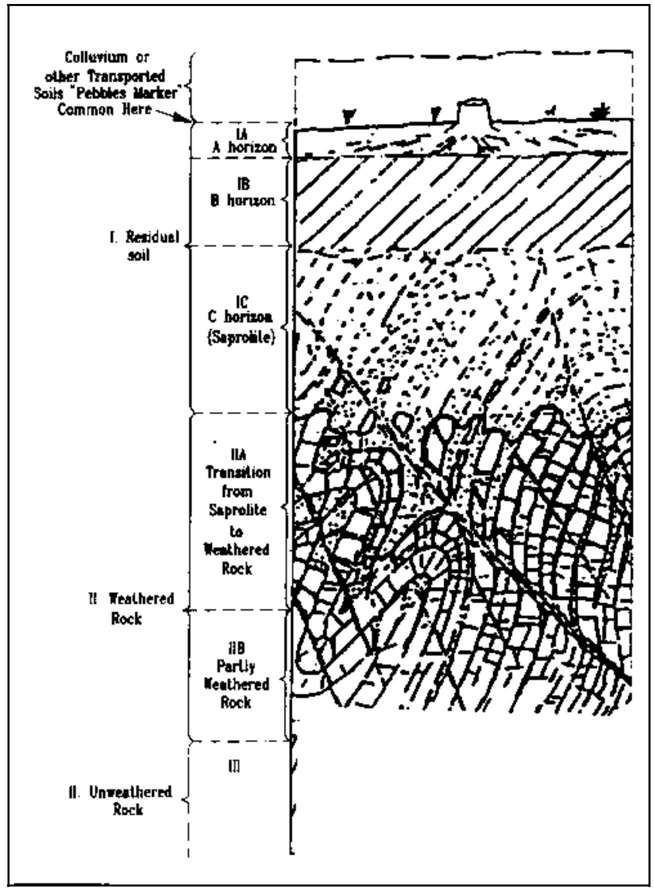

Figure 12-5. Typical weathering profile for metamorphic rocks (from Deere and Patton 1971)

develop into a profile, as illustrated in Figure 12-6, with sharp contacts between soils and weathered rock, unlike igneous, and metamorphic profiles. Occasionally, carbonate rocks may have chert, sand, or clay which form saprolite and retain a relict structure upon weathering. In most cases, however, the carbonates are removed and the remaining insoluble residue, typically a dark red clayey "terra rosa," lies directly upon weathered rock. A jagged, pinnacled rock surface may develop due to weathering along faults or near-vertical joints. Troughs between the peaks may contain soft, saturated clays called "pockets of decalcification." Construction problems may include clayey seams, soft clays, rough bedrock surface, unstable collapse residuum, and rock cavities.

e. Shale profile. Shale weathering profiles also develop primarily along joints and fissures, but the weathering profile is generally thinner and the transition from soil to unweathered rock tends to be more gradual. Shale is generally composed of minerals which are the weathering by-products of other rocks, so under a new weathering environment they are not affected to the extent other rocks are. Mechanical weathering mechanisms, such as drying and rewetting, freeze-thaw cycles, and stress relief play a more important role in the development of a shale weathering profile, so increased fracturing is the characteristic of increasingly weathered shale. Interbedded sandstones tend to make the weathering patterns and overall stability problems more complex. For engineering design purposes, the handling of shale excavations grades from rock mechanics into soil mechanics, where most weathered shales can be treated as consolidated clays.

12-14. Design Considerations in Weathering Profiles

During subsurface investigations, saprolites most likely are classified as soils, since the samples recovered by subsurface drilling programs frequently end up as a

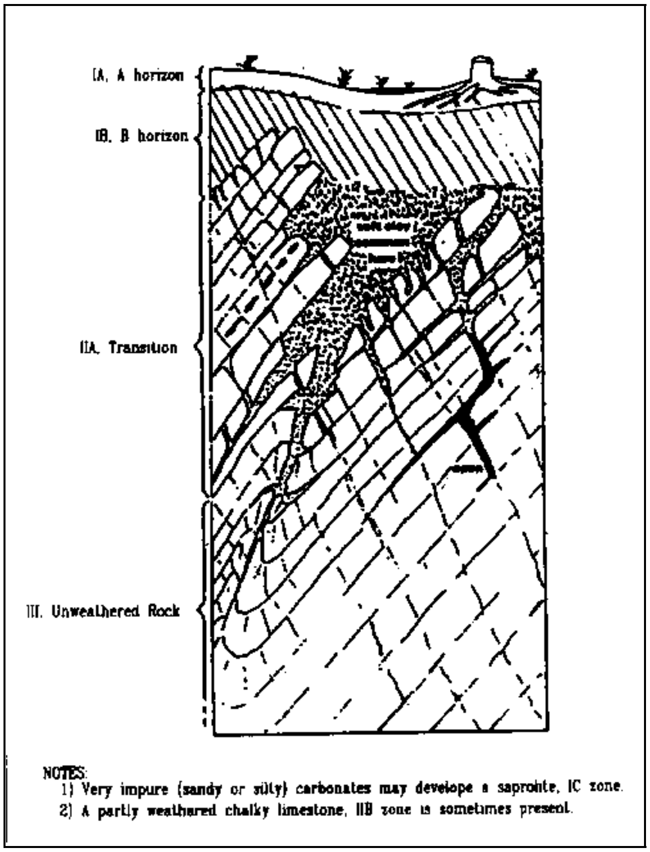

Figure 12-6. Typical weathering profile for carbonate rocks (from Deere and Patton 1971)

disaggregated, crumbly material with no apparent structure. The sampling technique frequently destroys the interparticle bonding and gives the designer a poor idea of the actual conditions. Care should be taken during sampling to determine if saprolites and relict structures exist if they will be exposed in rock excavations. Trenching provides a better picture of the weathering profile in critical areas.

a. Saprolites. Since relict discontinuities may exist in saprolite zones, sliding or toppling of weak blocks may be difficult to evaluate in stability analyses. In some cases, studies using key-block theory (Goodman and Shi 1985) may be applicable to saprolites. The discontinuities may also be the principal permeability path for ground water in saprolites, and water pressure in relict joints may play a substantial part in excavation stability. For design purposes, saprolites should be considered a weak, blocky, seamy rock in which discontinuities govern the behavior. For excavation purposes, saprolites may be treated as a firm soil, requiring standard soil excavation techniques.

b. Transition materials. Below the saprolites in the weathering profile, the nature of the materials is more difficult to determine. The materials may act as a soil matrix with rock fragments of lesser importance, a rock mass with soil-like, compressible seams, or some intermediate material. The primary concern is the thickness compressibility or stability of the soil-like material between core-blocks or in seams, which governs the behavior of the material to a larger degree than the more easily recovered competent rock. In addition, rock in these zones may have an irregular surface, but may be adequate for load bearing. These conditions may require removal of all pinnacles to a prescribed suitable depth, or cleaning out of the crevices and backfilling with dental concrete. Lightly loaded footings on seamy rock may be adequate if the footings are expanded to prevent eccentric loading on individual blocks. If settlements are anticipated to be excessive using these techniques, drilled piers extending to competent rock at depth may be an economic alternative.